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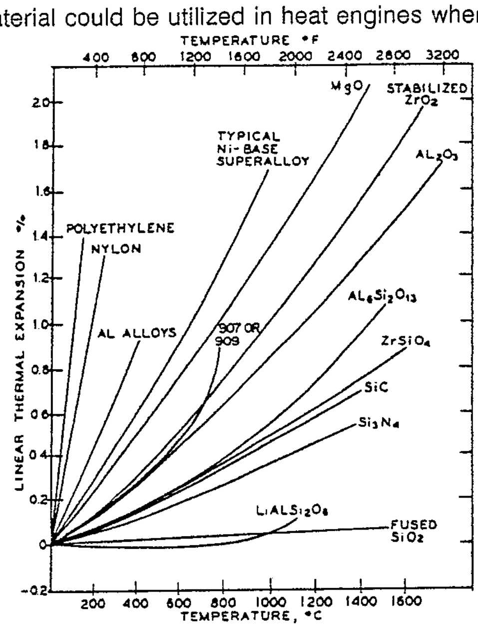
(54) Low coefficient of expansion alloys having a thermal barrier coating.

(57) A low coefficient of expansion alloy is coated with a thermal barrier coating having a low coefficient of expansion compatible with the alloy. The alloy is preferably a chromium-free iron-base alloy and is fist coated with an oxidation reistant intermediate bond coating and then with a zirconia containing thermal barrier. An article of manufacture made from this material could be utilized in heat engines where close tolerances are required.



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LOW COEFFICIENT OF EXPANSION ALLOYS HAVING A THERMAL BARRIER

The instant invention relates to a thermal barrier coating system in general, and more particularly, to a thermal barrier coating system for alloys having a low coefficient of expansion.

In order to increase the efficiency of heat engines, such as gas turbines and reciprocating engines, there usually must be a concomitant increase in the operating temperatures and pressures of these devices. Unfortunately, most current materials systems ultimately fail at elevated conditions thereby causing a practical limit on operating parameters.

Over the years various materials have been proposed and introduced to boost the operating temperatures and pressures of these engines. One common system includes the application of a thermal barrier coating ("TBC") including zirconia to a superalloy substrate. An intermediate oxidation resistant bond coating of MCrAlY is disposed between the TBC and the substrate.

The thermal expansion mismatch between conventional superalloys and their ceramic TBC's is partially accommodated by deliberately making the ceramic coating 10% porous. This is a half step at best. Under the circumstances, zirconia has been the material of choice since its coefficient of expansion is somewhat similar to those of the available nickel-base and cobalt-base superalloys now in production. In addition ZrO_2 has the lowest thermal conductivity of the common refractory materials. MgO and Al_2O_3 are not very suitable because their thermal conductivities are much greater than ZrO_2.

A difficulty with the available systems is that the superalloys have a moderate coefficient of expansion that must be taken into account when the internal components of the engines are fabricated. In jet aircraft engines, for example, turbines may reach temperatures of 1093 °C (2000 °F) and more. Although the refractory coating enables the superalloys to operate within such an environment serving as both a thermal barrier as well as an adjunct to the corrosion resistant properties of the alloy, the expansion of the superalloy substrate material may introduce certain inherent design inefficiencies in the engine. Close operating tolerances of the critical components are absolutely critical in turbine design.

As a result of the extreme conditions encountered in such power plants, low coefficient of expansion alloys have not been generally used in the more critical areas. Although possessing wonderfully low coefficient of expansion values which would allow increased engine component tolerances, these alloys generally do not exhibit the requisite high temperature and corrosion resistant characteristics as do the nickel-base and cobalt-base superalloys.

Low expansion cast and wrought alloys such as the 900 series of iron-base alloys are used for shafts, seals and shrouds in gas turbine engines where they are limited to components operating at 649 °C (1200 °F) or lower. This is because of the reduced oxidation resistance at this temperature and above. The problem is further compound by the fact that at temperatures above about 649 °C (1200 °F) the alloys undergo phase changes that embrittle them. However, as discussed above, to improve engine efficiency through tighter sealing, gas turbine manufacturers would welcome the opportunity to extend the use of low expansion alloys to higher operating temperatures and pressures, but currently are stymied in view of the perceived shortcomings of the alloys.

There are numerous coating systems in the literature. U.S. Patents 4,055,705; 4,248,940; 4,255,495; 4,485,151; 4,535,037; 4,375,190 are associated with refractories deposited on superalloy substrates.

The present invention provides a low expansion alloy having an oxidation resistant, thermal barrier duplex coating. More particularly, it provides a coated article of manufacture having a thermal barrier coating system comprising a substrate made from a low coefficient of expansion alloy; an oxidation resistant intermediate bond coating registered with the substrate; and a thermal barrier coating over the intermediate bond coating exhibiting a coefficient of expansion compatible with the substrate. The thermal barrier coating may include yttria and may be a partially stabilized zirconia-yttria thermal barrier coating.

The resultant system exhibits the necessary low expansion characteristics and superalloy properties while simultaneously providing satisfactory oxidation resistance. Articles of manufacture may withstand temperatures of about 871 °C (1600 °F). Higher temperatures may be withstood provided that air cooling is employed.

The thermal barrier coating has a very low thermal conductivity and a coefficient of expansion acceptably compatible to the cast and wrought low coefficient of expansion alloys in the expected temperature ranges. Although the anticipated internal operating temperatures may be higher than the results herein, the insulating characteristics of the thermal barrier will reduce the temperature of the substrate to acceptable levels.

The invention will now be described in more detail with reference to the accompanying drawing, which shows graphically the linear thermal expansion (in percent) of various materials versus temperature.

The ultimate thrust of the instant invention is the increased utilization of low coefficient of expansion iron-base alloys, more particularly the 900 series of alloys, in heat engines. By applying the refractory thermal barrier and the intermediate bond layer to the alloy, the alloy's low expansion characteristics may be used to great advantage. The thermal barrier, preferably a partially stabilized zirconia ("PSZ" - 8% Y_2O_3-ZrO_2) fairly matches the coefficent of expansion of the substrate 900 series of alloys, (903, 907 and 909) and is compatible therewith. By insulating the substrate from the high internal temperature ravages of the engine, the components made from the instant invention may permit closer manufacturing tolerances thereby resulting in greater operating efficiencies.

The 900 series of alloys nominally contain about 38% nickel, 13-15% cobalt, 3-4.5% or 4.7% niobium, 1.4-1.5% titanium, optional silicon (up to about 0.4%) and aluminum (up to about 0.9%), small quantities of other materials depending on the formulation and the remainder essentially iron (42%). The nominal compositions of the individual alloys of the 900 series (available as INCOLOY alloys 903, 907 and 909 [trademark of the applicant company]) are as follows:-

Alloy	Ni %	Co %	Ti %	Al %	Si %	Nb %	Fe(bal) %
903	38	15	1.4	0.7(0.9)	-	3	41.5
907	37.4(38)	13	1.5	0.1(0.03)	0.1(0.15)	4.7	42
909	37.4(38)	13	1.5	0.1(0.03)	0.4	4.7	42.7

These alloys are the subject respectively of US-A-3 157 495 (Alloy 903), US-A-4 200 459 (Alloy 907) and US-A-4 487 743 (Alloy 909), in which further details of their compositions are given. To achieve the low coefficient of expansion ("COE"), the chemistry is restricted. In particular, chromium is substantially absent and aluminum must be limited to levels normally less than contained in other classes of superalloys. Normally this will cause oxidation at elevated temperatures as well as a rise in the COE. However, by coating these materials, oxidation resistance is maintained and temperature stresses within the substrate are kept to acceptable levels.

In particular, the 900 series of iron-base alloys were developed to take advantage of their low COE. For example, the COE of alloy 909 is about 10.3 μm/m/°C (5.7 x 10^{-6} in/in/°F) at about 649°C (1200°F) whereas the nickel-base superalloys INCONEL alloy 718 (trademark of the applicant company), RENE 41 (trademark of Teledyne Allvac) and WASPALOY (trademark of United Technologies Corp.) have a combined average COE of about 15.3 μm/m/°C (8.5 x 10^{-6} in/in/°F) at 649°C (1200°F) (about 48% higher than 909). Iron-base superalloy A-286 has a COE of about 17.6 μm/m/°C (9.8 x 10^{-6} in/in/°F) at 649°C (1200°F) (about 71% higher than 909).

The Figure provides a comparison between various materials. It should be noted that the low expansion 900 series of alloys (particularly 907 and 909) are closer to zirconia than the typical nickel-base (and iron- and cobalt-base) superalloys. For example, the COEs for alloys 907 and 909 at -18 to 93°C (0-200°F) are about 8.0μm/m/°C (4.46 x 10^{-6} in/in/°F). The COE of PSZ at this same temperature range is about 11.0 μm/m/°C (6.1 x 10^{-6} in/in/°F). The COE's at the temperature of interest are similar since they do not appreciably change.

The coatings may be applied to the substrate by techniques known and available to those in the art. Plasma spraying was utilized in obtaining the following data. A METCO® 9MB plasma spray unit was employed. It should be appreciated, however, that the other suitable methods of applying the thermal barrier and intermediate bond coating are appropriate as well.

MCrAlY (M = Ni, Fe, Co, NiFe, NiCo or mixtures thereof) was preferentially selected for the bond coating since it is highly effective for essential oxidation resistance. MCrAl and MAl may also be utilized if the conditions are less demanding.

For the purposes of this specification a low COE is meant to be a value at least 25% lower than a corresponding nickel, iron or cobalt-base superalloy or an article of manufacture made therefrom at a given temperature.

Test specimens were prepared. In most instances low COE INCOLOY® alloy 909 was the substrate alloy. For the purposes of comparison, INCOLEN® alloy 718 and INCOLOY® alloy 800 were used for five substrates. The powders used for the intermediate bond coating were procured from commercial sources. Table I lists the compositions for the substrates and the intermediate bond coating.

TABLE I

COMPOSITION OF SUBSTRATES AND INTERMEDIATE LAYERS									
Alloy Substrates	Ni	Co	Fe	Cr	Cb	Ti	Al	Si	Other
909	38.2	13.0	Bal.	--	4.7	1.5	0.03	0.4	--
718	52.0	1.0 max.	Bal.	19.0	5.2	0.8	0.5	0.35 max.	--
800	32.0	--	Bal.	21.0	--	0.4	0.4	1.0 max.	--
Intermediate Layers									
Ni 211	Bal.	--	Bal.	22.0	--	--	10.0	--	1Y
Fe 124	--	--	Bal.	24	--	--	8	--	.5Y
Ni 963	60.0	--	Bal.	22.5	--	--	6.8	--	--

Tables II and III list the particulars of the specimens. Table II relates to the entire system, whereas Table III details three different thermal barrier coating compositions.

TABLE II

COMPOSITION OF TEST PIN SERIES				
Sample No.	8% Y_2O_3 - ZrO_2 microns (mils)	Type of PSZ Powder	Intermediate Layer microns (mils)	Type of Powder
0	500 (20)	Sintered	100 (4)	Ni 211
1	500 (20)	Fused	100 (4)	Fe 124
2	500 (20)	Fused	100 (4)	Fe 124
3	500 (20)	Fused	100 (4)	Fe 124
4	500 (20)	Sintered	100 (4)	Fe 124
5	500 (20)	Sintered	100 (4)	Fe 124
6	500 (20)	Sintered	100 (4)	Fe 124
7	500 (20)	Fused	100 (4)	Ni 211
8	500 (20)	Fused	100 (4)	Ni 211
9	500 (20)	Fused	100 (4)	Ni 211
10	500 (20)	Sintered	100 (4)	Ni 211
11	500 (20)	Sintered	100 (4)	Ni 211
12*	500 (20)	Sintered	100 (4)	Ni 211
16**	500 (20)	Fused	10 (0.4)	Ni 963
19	500 (20)	Fused	100 (4)	Ni 211
20	500 (20)	Fused	100 (4)	Ni 211
21	500 (20)	Sintered	100 (4)	Ni 211
22	1000 (40)	Sintered	100 (4)	Ni 211
23	2000 (80)	Sintered	100 (4)	Ni 211
30	500 (20)	Sintered	200 (8)	Ni 211
31	1000 (40)	Sintered	200 (8)	Ni 211
32	2000 (80)	Sintered	200 (8)	Ni 211
37	1000 (40)	Sintered	100 (4)	Ni 211
39	1000 (40)	Sintered	200 (8)	Ni 211
42	1000 (40)	Sintered	100 (4)	Ni 211
All domed pin substrates are INCOLOY® alloy 909 (about 12.7 mm [0.5 in] diameter x 76.2 mm [3.0 in] long) except 19, 20, 37 and 38 which were INCONEL® alloy 718 and 42 which was INCOLOY® alloy 800.				

*Pin #12 was machined to hollow (6.3 mm [0.25 in] diameter) the interior to the dome of the pin

**Intermediate layer was a plasma vapor coated deposition (PVD)

TABLE III

COMPOSITION OF VARIOUS TYPES OF PARTIALLY STABILIZED ZIRCONIA MONOLITHS			
Monolith No.	Composition		Type
M- 2	8%	Y_2O_3 - ZrO_2	Fused and crushed
M- 5	8%	Y_2O_3 - ZrO_2	Sintered and crushed
M- 7	8%	Y_2O_3 - ZrO_2	Spherodized
M-10	12%	Y_2O_3 - ZrO_2	Fused and crushed
M-11	12%	Y_2O_3 - ZrO_2	Fused and crushed
M-13	20%	Y_2O_3 - ZrO_2	Fused and crushed

The specimens were evaluated in a cyclic oxidation rig under a variety of conditions aimed at evaluating: (i) the comparative resistance to thermal fatigue (coating crack or spalling) in order to find the preferred coating system; (ii) the operating temperature below which failure does not occur and (iii) the temperature gradient across the thermal barrier coating.

The monoliths of Table III were made by spraying the various PSZ powders on a 12.5 mm (.5 in) diameter x 76.2 mm (3 in) length copper substrate followed by acid dissolution of the copper.

The thermal cycling data from the specimens are presented by test run in Table IV. Each test run varied in thermal conditions and duration, consequently the data are reported by Test Run number (TR). The monoliths (second series of specimens) are described in Table V along with the distribution of phases in the as-received condition. Data from Table IV are presented in Table VI to show the effect of furnace temperature on the thermal cycle resistance of both types of PSZ (fused and sintered) coatings of FeCrAlY and NiCrAlY intermediate layers using an INCOLOY® alloy 909 substrate. Table VII summarizes the sustainable temperature gradient as measured at different operating temperatures and the thermal cycle history of air cooled (0.2 m^3/hr [8 ft^3/hr]) hollow pin 12. A more detailed sustainable temperature gradient versus environmental temperature is given in Table VIII for pin 12. These temperature values are not rounded. Table IX compares the thermal cycle resistance of sintered PSZ coating on Ni 211 intermediate layer on INCOLOY® alloy 909 versus INCONEL® alloy 718 substrates at two furnace temperatures. Table X shows the effect of sintered PSZ thickness on two thicknesses of Ni 211 intermediate layer of INCOLOY® alloy 909 at a furnace temperature of 1000 °C (1830 °F). Table XI presents the thermal cycle resistance of INCOLOY® alloy 909 substrate versus INCONEL® alloy 718 and INCOLOY® alloy 800 substrates at equivalent sintered PSZ coating and Ni 211 intermediate layer thicknesses at 1000 °C (1830 °F).

TABLE IV

THERMAL CYCLE RESISTANCE OF PSZ COATED PINS

TR 1

Conditions:

Furnace temperature:	915°C (1680°F)
Temperature at Core of Pin in Furnace:	700°C (1290°F)
Temperature at Core of Pin out of Furnace:	205°C (400°F)
Cycle Times:	15 min. in furnace/ 5 min. out

Pin No.	Results
0	4536 cycles (63 days) without failure. Metallographic sample taken and pin 0 restarted in TR 4.

TR 2

Conditions:

Furnace temperature	900°C (1650°F)
Temperature at Core of Pin in Furnace:	820°C (1510°F)
Temperature at Core of Pin out of Furnace:	205°C (400°F)
Cycle Times:	30 min. in furnace/ 10 min. out

Pin No.	Results
1	Failed in 1152 cycles (32 days) with longitudinal cracks and peeling from exposed end.
4	Failed in 1260 cycles (35 days) similar to Pin 1.
7	Failed in 1260 cycles (35 days) minor longitudinal crack emanating from exposed end.
10	No failure after 1260 cycles (35 days) Pin 10 restarted in TR 4

TABLE IV (CONT'D.)

TR 3

Conditions:

Furnace temperature:	880°C (1610°F)
Temperature at Core of Pin with Air Flowing:	740°C (1365°F)
Temperature of Core of Pin without Air Flowing:	820°C (1510°F)
Temperature of Core of Pin with Air Flowing and Outside of Furnace:	70°C (160°F)
Cycle Times:	30 min. in furnace/ 10 min. out

Pin No.	Results
12 (Air Cooled)	No failure after 1044 cycles (29 days) Pin 12 restarted in TR 6

TR 4 AND 5

Conditions:

Furnace temperature:	900°C (1650°F)
Temperature at Core of Pin in Furnace:	820°C (1510°F)
Temperature at Core of Pin out of Furnace:	205°C (400°F)
Cycle Times:	15 min. in furnace/ 5 min. out

Pin No.	Results
0	396 cycles then restarted in TR 6.
10	Failed after 324 cycles (9 days) with hairline longitudinal crack - total of 1584 cycles (TR 2 and TR 4).
16	Failed after 144 cycles (4 days) with extensive longitudinal cracks.
19 (718 substrate)	Failed after 360 cycles (10 days).

TR 6

Conditions:

Furnace temperature:	1015°C (1860°F)
Temperature at Core of Pin in Furnace:	980°C (1795°F)
Temperature at Core of Pin out of Furnace:	135°C (275°F)
Temperature of Core of Pin 12 in Furnace:	910°C (1670°F)
Temperature of Core of Pin 12 outside Furnace:	70°C (160°F)
Cycle Times:	30 min. in furnace/ 10 min. out 1

TABLE IV (CONT'D.)

Pin No.	Results
0	Failed in 144 cycles (cracks at bottom) - total of 5076 cycles (TR's 1, 4 and 6).
3	Failed in 72 cycles (2 days) with longitudinal cracks.
5	Slight peeling at bottom after 216 cycles (6 days) - restarted Pin 5 in TR 7.
9	Failed in 72 cycles (2 days) with longitudinal cracks.
11	Ran 216 cycles (6 days) with no failure - restarted Pin 11 in TR 7.
17	Failed in 7 cycles (0.2 day) with massive spalling at PSZ coating.
20 (718 substrate)	Failed at 72 cycles (2 days) with crack on dome.
12 (Air Cooled)	No failure in 144 cycles (4 days) - restarted Pin 12 in TR 7.

TR 7

Conditions:

Furnace temperature:	650°C (1200°F)
Temperature at Core of Pin in Furnace:	640°C (1185°F)
Temperature at Core of Pin out of Furnace:	205°C (400°F)
Temperature of Core of Pin 12 in Furnace:	490°C (900°F)
Temperature of Core of Pin 12 out of Furnace:	70°C (160°F)
Cycle Times:	30 min. in furnace/ 10 min. out

Pin No.	Results
2	No failure after 1877 cycles (52 days).
5	Failed after 390 cycles (11 days) with cracks on dome and bottom area (plus 216 cycles (6 days) in TR 6.
6	No failure after 1877 cycles (52 days).
8	No failure after 1877 cycles (52 days).
11	No failure after 1877 cycles (52 days) plus 216 cycles (6 days) in TR 6.

TABLE IV (CONT'D.)

Pin No.	Results
12 (Air Cooled)	Cracks on dome after 595 cycles (17 days). Cracks first observed at 390 cycles (11 days). Pin 12 had total 1783 cycles (50 days) in TR's 3, 4, 6 and 7. Pin 12 restarted in TR6.

TR 4 AND 5 COMBINED

Conditions:

Furnace temperature:	900°C (1650°F)
Temperature at Core of Pin in Furnace:	820°C (1510°F)
Temperature at Core of Pin out of Furnace:	205°C (400°F)
Cycle Times:	15 min. in furnace/ 5 min. out

TR 8

Conditions:

Furnace temperature:	1000°C (1830°F)
Temperature at Core of Pin in Furnace:	994°C (1830°F)
Temperature at Core of Pin out of Furnace:	205°C (400°F)
Cycle Times:	60 min. in furnace/ 10 min. out

Pin No.	Results
21	No failure after 750 cycles (36 days).
22	Crack on dome at 190 cycles (9 days) (no propagating after 750 cycles [36 days]).
23	Failed at 25 cycles (1 day).
30	No failure after 750 cycles (36 days).
31	Failed at 40 cycles (2 days).
32	Failed at 25 cycles (1 day).
37 (718 substrate)	Failed at 41 cycles (2 days).
39 (718 substrate)	Failed at 21 cycles (1 day).
42 (800 substrate)	Failed at 39 cycles (2 days).

TABLE V

PHASE IDENTIFICATION OF PLASMA SPRAYED MONOLITHS					
Monolith No.	Type PSZ		Phase Distribution		
			Tetragonal	FCC	Monoclinic
M- 2	8%	Y_2O_3 PSZ-Fused	100%	--	--
M- 5	8%	Y_2O_3 PSZ-Sintered	100%	--	--
M- 7	8%	Y_2O_3 PSZ-Spheroidized	100%	--	--
M-10	12%	Y_2O_3 PSZ-Fused	57%	43%	--
M-11	12%	Y_2O_3 PSZ-Fused	41%	59%	--
M-13	20%	Y_2O_3 PSZ-Fused	--	100%	--

TABLE VI

EFFECT OF FURNACE TEMPERATURE ON THERMAL CYCLE RESISTANCE OF FUSED AND SINTERED PSZ COATINGS ON FeCrAlY and NiCrAlY INTERMEDIATE LAYERS USING AN INCOLOY® ALLOY 909 SUBSTRATE				
TBC Type	Intermediate Layer	Cycles @ 650 °C(1220 °F)	Cycles @ 910 °C(1670 °F)	Cycles @ 1015 °C(1860 °F)
Fused	Fe 124	>1877	1052	72
Sintered	Fe 124	>1877	1186	208
Fused	Ni 211	>1877	1160	72
Sintered	Ni 211	>1877	5076	216*

*Initially 360 cycles at 650 °C (1200 °F)

TABLE VII

HISTORY OF AIR COOLED (0.2 m^3/hr [8 ft^3/hr]) PIN #12				
TR	Furnace, °C (°F)	Core, °C (°F)	Difference, °C (°F)	# Cycles
3	880 (1610)	740 (1365)	140 (245)	1044
6	1015 (1860)	910 (1670)	105 (190)	144
7	650 (1200)	505 (940)	145 (260)	595

TABLE VIII

SUSTAINABLE TEMPERATURE GRADIENT EXPERIENCED BY PIN #12 VERSUS ENVIRONMENTAL TEMPERATURE USING INTERNAL AIR FLOW OF 0.2 m^3/hr (8 ft^3/hr)		
Furnace Temperature, °C (°F)	Core Temperature, °C (°F)	Difference, °C (°F)
1019 (1866)	916 (1680)	103 (186)
890 (1634)	742 (1368)	148 (266)
809 (1488)	650 (1202)	159 (286)
719 (1325)	556 (1032)	163 (293)
604 (1120)	440 (824)	164 (296)

TABLE IX

THERMAL CYCLE RESISTANCE OF SINTERED PSZ COATING ON NiCrAlY (Ni 211) INTERMEDIATE LAYER ON INCOLOY® ALLOY 900 VERSUS INCONEL® ALLOY 718 SUBSTRATES AT 900°C (1650°F) AND 1015°C (1860°F)		
Furnace Temperature, °C (°F)	Cycles to Failure	
	Alloy 909	Alloy 718
900 (1650)	5076	360
1015 (1860)	216*	72

*360 cycles initially at 650°C (1200°F)

TABLE X

EFFECT OF SINTERED PSZ THICKNESS ON TWO THICKNESSES OF NiCrAlY (Ni 211) INTERMEDIATE LAYER ON INCOLOY® ALLOY 909 AT FURNACE TEMPERATURE OF 1000°C (1830°F)			
Pin No.	Ni 211 Thickness microns (mils)	Sintered PSZ thickness, microns (mils)	Cycles to Failure
21	100 (4)	500 (20)	700
22	100 (4)	1000 (40)	190 (minor crack on dome)
23	100 (4)	2000 (80)	25
30	200 (8)	500 (20)	700
31	200 (8)	1000 (40)	40
32	200 (8)	2000 (80)	25

TABLE XI

COMPARISON OF THERMAL CYCLE RESISTANCE OF INCOLOY® ALLOY 909 VERSUS INCONEL® ALLOY 718 AND INCOLOY® ALLOY 800 SUBSTRATES AT EQUIVALENT SINTERED PSZ COATING AND NiCrAlY (Ni 211) INTERMEDIATE LAYER THICKNESS AT 1000°C (1830°F)

Pin No.	Substrate	Ni 211 thickness microns (mils)	Sintered PSZ thickness microns (mils)	Cycles to Failure
22	909	100 (4)	1000 (40)	190 (minor crack on dome)
37	718	100 (4)	1000 (40)	41
42	800	100 (4)	1000 (40)	39
31	909	200 (8)	1000 (40)	40
39	718	200 (8)	1000 (40)	21

The results demonstrate: (i) the compatibility of duplex PSZ coating with low COE alloys, particularly 909 and (ii) that duplex PSZ coated INCOLOY® alloy 909 can be used in higher temperature environments than uncoated INCOLOY® alloy 909. It has been additionally shown that thermal barrier coated INCOLOY® alloy 909 as a composite system has greater thermal cycle resistance than does thermal barrier coated INCONEL® alloy 718 or thermal barrier coated INCOLOY® alloy 800. The instant system has been shown to tolerate at least up to 871°C (1600°F) with an air flow of only 0.2 m^3/hr (8 ft^3/hr) for at least 5000 cycles. It outperformed an identically tested alloy 718 NiCrAlY bond coat/PSZ composite which failed in less than 400 cycles.

Table IV presents the thermal cycle resistance of the composite specimens tested under a variety of thermal cycle conditions. The tests were run in order to select a preferred type of 8% Y_2O_3-ZrO_2 (fused or sintered) and a preferred choice for MCrAlY intermediate layer (M = Ni or Fe). Additionally, four duplicate coated pins with INCONEL® alloy 718 substrates were tested for comparative purposes with INCOLOY® alloy 909. One plasma vapor deposited ("PVD") intermediate layer on INCOLOY® alloy 909 was also evaluated. The results (Table VI) suggest that at temperatures near 910°C (1670°F) and above sintered PSZ is preferably to fused PSZ. The reason for the preferred performance is not yet known. Similarly as shown also in Table VI, the performance of the two intermediate layers (NiCrAlY and FeCrAlY) are equivalent at 650°C (1220°F). However, at 910°C (1670°F) and above, the NiCrAlY intermediate layer (Ni 211) is preferred over the FeCrAlY intermediate layer (Fe 124). Again, a reason for this result has yet to be established. Table X clearly shows the marked improvement in thermal cycle resistance that is achieved when INCOLOY® alloy 909 is used as the substrate for a sintered PSZ coating (0.5 mm [0.02 in]) on a NiCrAlY (Ni 211) (0.1 mm [0.004 in]) intermediate layer over that of the duplicate coating on INCO alloy 718 (see Table XI for additional comparison with INCONEL® alloy 718 and INCOLOY® alloy 800). The PVD coating of Ni 963 was not roughened prior to either PVD or plasma spraying (of PSZ coating), consequently, the composite failed rapidly (Pin 16 in TR 4 and 5, data presented in Table IV).

The effect of PSZ coating thickness on thermal cycle resistance is shown in Table X using the pins described in Table II. The 0.5 mm (20 mils) coating is preferred over the thicker coating thicknesses. These same Tables (X and II) present data to suggest that there is essentially no difference in performance between 0.1 mm (4 mils) and 0.2 mm (8 mils) NiCrAlY intermediate layer thicknesses.

Zirconia undergoes a drastic phase change near 950°C upon cooling which results in a 3.5% volume expansion. Additions of Y_2O_3 (6-8%) initially stabilize the high temperature tetragonal phase to much lower temperatures. Compositions near 12% Y_2O_3-ZrO_2 are 50% tetragonal - 50% FCC, while those near 20% Y_2O_3-ZrO_2 are totally FCC. This is confirmed in Table V for the monoliths of Table III. Note that the type of 8% Y_2O_3-ZrO_2 does not alter the phase distribution.

Pin #12 from Table II was machined with a 6.3 mm (0.25 in) drill to make a hole to the dome of the test pin and using a small diameter tube and laboratory compressed air at 0.2 m^3/hr (8 ft^3/hr), the pin was air cooled while being tested in TR's 3, 6 and 7. The sustained temperature gradient and number of thermal cycles at each test temperature are given in Table VIII and a profile of the sustainable temperature gradients from 604°C (1120°F) to 1019°C (1866°F) are given in Table IX. Note that the sustainable temperature gradient gradually decreases as the temperature increases for the 0.5 mm (0.02 in) PSZ coating. Nonetheless, air cooled engine components made from the materials disclosed herein appear to be acceptable and overcome the difficulties envisioned with conventional 900 series alloys.

While specific embodiments of the invention are illustrated and described herein, those skilled in the art will understand that changes may be made in the form of the invention covered by the claims and that certain features of the invention may sometimes be used to advantage without a corresponding use of the other features.

Claims

1. A coated article of manufacture having a thermal barrier coating system comprising a substrate made from a low coefficient of expansion alloy; an oxidation resistant intermediate bond coating registered with the substrate; and a thermal barrier coating over the intermediate bond coating exhibiting a coefficient of expansion compatible with the substrate.

2. An article according to claim 1 wherein the substrate is an iron-base alloy.

3. An article according to claim 1 or 2 wherein the substrate is an alloy having the nominal composition about 38% nickel, 13-15% cobalt, 3-4.7% niobium, 1.4-1.5% titanium, optional silicon (up to about 0.4%) and aluminum (up to about 0.9%), balance, apart from impurities, iron (about 42%).

4. An article according to claim 3 wherein the substrate includes about 38% nickel, 13% cobalt, 4.7 niobium, 1.5% titanium, up to 0.4% silicon, up to 0.1% aluminum, and 42% iron.

5. An article according to claim 2 wherein the intermediate bond coating includes MCrAlY, MCrAl or MCr wherein M is selected from the group consisting of Ni, Fe, Co and mixtures thereof.

6. An article according to any preceding claim wherein the thermal barrier includes yttria.

7. An article according to any preceding claim wherein the thermal barrier includes sintered partially stabilized zirconia.

8. An article according to claim 7 wherein the thermal barrier includes 8% Y_2O_3-ZrO_2.

9. An article according to claim 4 including a NiCrAlY intermediate coating and a sintered partially stabilized zirconia thermal barrier.

10. An article according to claim 8 or claim 9 wherein the intermediate coating has a thickness of about 0.1 mm and the thermal barrier coating has a thickness of about 0.5 mm.

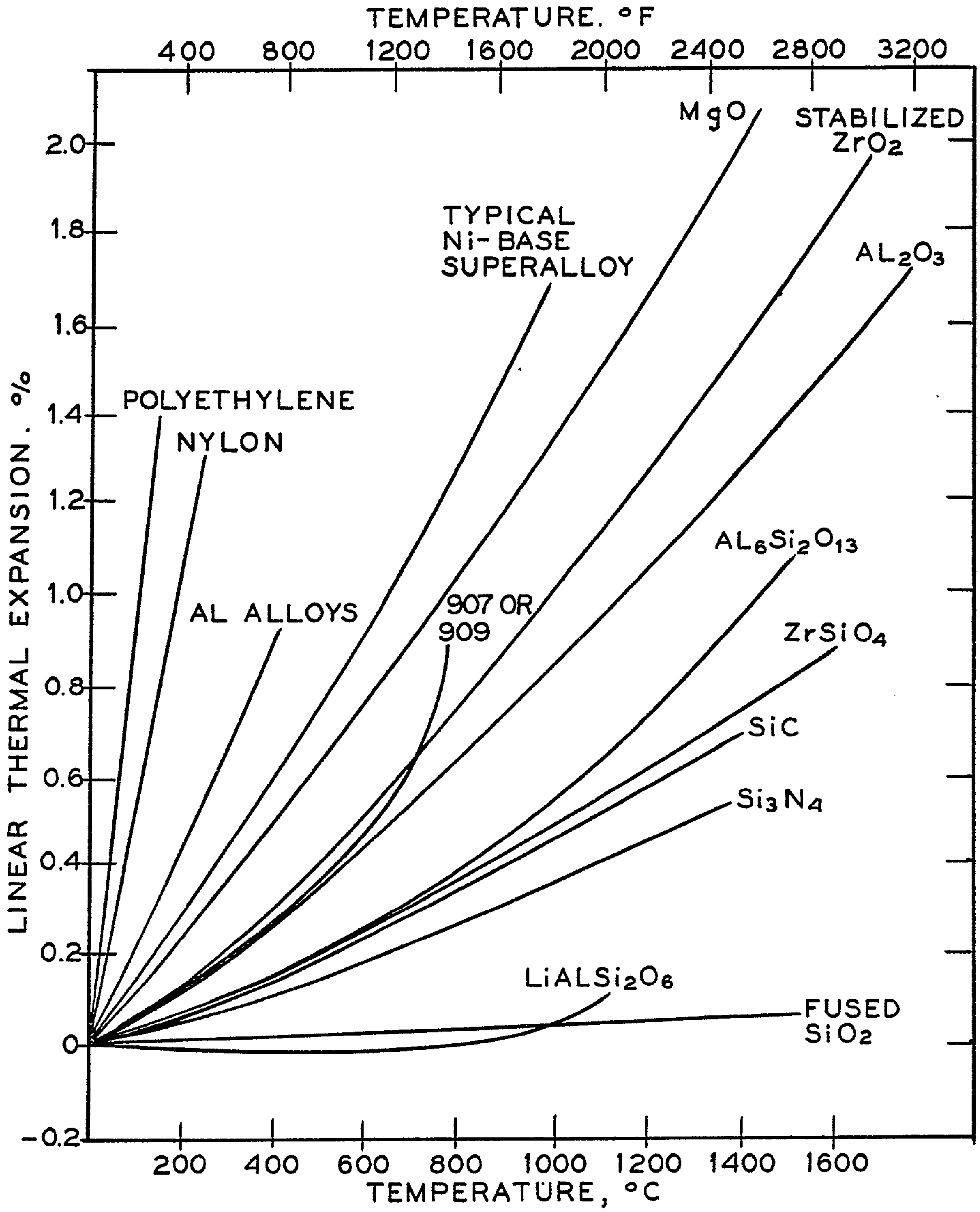
11. An article according to any preceding claim disposed in a heat engine.

12. An article according to any preceding claim adapted for internal cooling.

13. A method of fabricating an article having a thermal barrier coating, comprising the steps of coating a substrate of a low expansion alloy with an oxidation resistant bond coating and coating the bond coating with a thermal barrier coating having a low coefficient of expansion compatible with the substrate.

14. A method according to claim 13 wherein the bond coating and thermal barrier coating are applied by plasma spraying.

15. A method according to claim 13 or claim 14 wherein the article has the composition set forth in any one of claims 1 to 12.


TEMPERATURE. °F
400
800
1200
1600
2000
2400
2800
3200
LINEAR THERMAL EXPANSION. %
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
MgO
STABILIZED ZrO2
TYPICAL Ni-BASE SUPERALLOY
AL2O3
POLYETHYLENE
NYLON
AL ALLOYS
907 OR 909
AL6Si2O13
ZrSiO4
SiC
Si3N4
LiALSi2O6
FUSED SiO2
200
400
600
800
1000
1200
1400
1600
TEMPERATURE, °C

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 89 10 6952

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
X,D	US-A-4 485 151 (STEPHAN STECURA) * Abstract; column 1, lines 62-63; column 2, lines 17-37; column 4, lines 4-7,47-55; column 4, table II, column 5, lines 32-35; claims 1,2,4,5,7 *	1,2,5-8,10,11,13-15	C 23 C 4/02
A	US-A-4 576 874 (C.J. SPENGLER et al.) * Column 1, lines 60-64; column 3, lines 9-51; column 4, lines 1-9; claims 1,5 *	1,5-8,10,11,13-15	
A	WO-A-8 606 106 (PLASMAINVENT AG) * Abstract; page 5, lines 10-36; page 6, lines 6-21; page 8, lines 4-15 *	1,5,13-15	
A	EP-A-0 104 738 (HUNTINGTON ALLOYS INC.) * Abstract; page 3, lines 15-19 *	3,4	

TECHNICAL FIELDS SEARCHED (Int. Cl.4)

C 23 C
C 22 C

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	23-06-1989	JOFFREAU P.O.

CATEGORY OF CITED DOCUMENTS

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